Novel wide field-of-view laser retroreflector for the Space Interferometry Mission

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ABSTRACT

A new type of laser retroreflector has been developed for JPL's future Space Interferometry Mission. The retroreflector consists of an assembly of prisms to form multiple hollow cornercubes. This way the limited field of view (FOV) of about 60deg of a single corner can be overcome, to comply with the geometry of an optical truss. In addition, an innovative feature is that the retroreflector has common vertices, in order to define a single point optical fiducial necessary for point-to-point 3D laser metrology. The multiple cornercube provides better thermal stability and optical performance than spherical and hemispherical type retroreflectors. In manufacturing the prototype, the key technology of assembling prisms to the interferometric accuracy has been demonstrated. A non common vertex error of a few μm has been achieved.

Keywords: Interferometry, retroreflector, cornercube, optical fiducial, laser metrology, optical truss

1. INTRODUCTION

Spaceborne optical interferometry has been identified as a critical technology for many of NASA's 21st century science visions for probing the origins of stars and galaxies, and ultimately Earth-like planets around nearby stars. In these interferometers, optical elements are distributed on large structures to form large synthetic apertures. When doing astrometry, and to a less extent imaging, a laser metrology system is necessary to measure the positions and motions of these optics with a high accuracy. In stellar interferometers, like SIM [1], as well as in MAM [2] (the Micro Arcsec Metrology testbed, a prototype of SIM in a 10m vacuum chamber), the position of siderostat centers is of special interest because it defines the baseline and usually ties internal to external metrology. The purpose of external metrology is to monitor the position of the baseline defined by target fiducials which can be numerous. Measurements are done relative to referential fiducials. The reference shape is generically a tetrahedron-like structure which provides maximal 'optical rigidity'. The set of all fiducials defines an optical truss.

Both absolute and relative laser interferometers are used to measure the length or OPD of inter-fiducial segments with the aid of beam launcher heads situated in the path of each segment [3]. Segments, typically between one and ten meters long in JPL's projects, are monitored by absolute metrology (providing typically an accuracy of 1 μm over 1m) and relative metrology (subnanometer resolution). Transverse performance will always be degraded compared to longitudinal performance because of the limited attack angles from the tetrahedron to the target. Therefore wider angles must be used which will influence retroreflector design.

2. NEED OF WIDE FOV RETROREFLECTORS

A single cornercube (SCC) offers an angular acceptance zone, or FOV, which is commonly a spherical triangle with 90degrees sides if the beam is infinitely small. But because of typical beam sizes and facet sizes (eg 5mm and 30mm), FOV's of about 60 to 70 degrees are typical. Therefore a cornercube can see its neighbors only if they are inscribed within this 60deg zone. All rays outside of this triangle will not be reflected. Of course, for a centered beam (direction [1,1,1]) a beam of maximal size can be returned with no vignetting. In SIM as well as in MAM, much wider angles are necessary, up to 180deg when the fiducial must see opposite points. Computations show that for the earlier design of SIM and MAM (where the reference truss is a tetrahedron) as well as for the current design, a single hollow cornercube cannot suffice. Wide angle FOV (>60 to 70deg) retroreflectors are needed.

3. SPHERICAL RETROREFLECTORS ?

Different categories of wide FOV retroreflectors already exist. Classification criteria include whether it has powered (sphere, parabolic) or all flat surfaces, presence or absence of a focus, whether it is has transmissive or all reflective optics, whether it retroreflects discrete angular directions or provides continuous angular coverage over 2 or 4 pi steradian, etc...

Most have been developed for 3D robotic metrology and industrial laser trackers in the form of spherical cat's eye and hemispheric types with domes [4,5]. These systems however are not adequate for the needs of subnanomater spaceborne metrology. Several problems exist:

1- The main drawback of domes and other hemispheric types is their transmissive character. In space interferometry, special care is taken so laser (and starlight as well) paths are as much in vacuum as possible. Solid transmissive optics create unacceptable OPD uncertainties and require demanding thermal control. An elegant design of a simple ball made out of an exotic glass of indice $n_\lambda=2$ is investigated in our group [3]. It has the property to focus a parallel beam onto the back surface locally reflective coated. A problem is that for a typical radius of 4cm, the light traverses 8cm of glass which is a serious problem, especially because the exotic glass has bad thermo-expansion (CTE) properties.
2- A byproduct of transmission is dispersion for multiple wavelengths (inherent to absolute metrology).
3- A serious problem for spherical systems, both transmissive and reflective, is their intrinsic spherical aberration. Cancellation has been tried with multiple domes made from different glasses [4] but other problems persist.
4- In most of these systems, a focus is created on a reflective surface (plane or spherical), which is a problem because of statistical averaging over a too small surface. A typical focused spot is 10 µm in diameter. Although a sphere can be polished to a sphericity of 1/10 µm, the optical surface is not flat enough. A minor spot excursion will create unacceptable and hard to calibrate OPD errors [5]. Also a 10 µm area is subject to coating defects or dust.
5- Finally in some cat's eyes types the returned wavefront varies strongly with attitude changes of the retroreflector as well as input beam shear, due to inherent design or manufacturing errors (eg non concentricity of domes).

The solution to *all* previous problems is an all-reflective optical fiducial, with a single vertex point, made out of low CTE glass, in the form of a *multiple hollow cornercube with common vertex*, now referred as MCC:

1- In reflective types, the glass can be low CTE like ULE™ or Zerodur™, ideally stable in temperature and time.
2- It is all reflective so the OPD is air or vacuum therefore no dispersion is created.
3- flat mirrors create no spherical aberration
4- The surface averaging is large (mm-cm) giving better subnanometer length measurement.
5- The returned wavefront is relatively less sensitive to tilts (attitude changes) and shear.

It is believed that a MCC cannot be made monolithic according to current technologies of molding, polishing or figuring. Hence several prisms must be made separately and then assembled accurately to form the hollow corners where laser beams will be reflected. Since transmission is not a concern here, the material can be the well-proven ULE or Zerodur. External facets are unimportant and the external shape could be a sphere. Three faces of each corner must be mutually orthogonal at the arcsecond level. The central vertex, actually virtual, is the intersection of all reflective faces. Each prism must be polished and coated on some given faces. Several angles are crucial. The achievement of the 90deg corners depends on the angular accuracy of individual prisms as well as assembly accuracy and operator skills, linked by angle closure considerations. The achievement of a low Non Common Vertex Error (NCVE) depends *only* on assembly, where accurate piston ajustements are needed. Even with perfect prisms, a NCVE can occur.

The returned wavefront quality is mainly limited by the quality (the flatness) of the three faces used for retroreflection, dihedral errors, and the diffraction of the gaps and bevels which can be made small if less than about 50µm. Is is important to note that in JPL metrology concepts, the metrology beams are illuminating cornercubes on their vertex (as opposed to a 3 face sequential bounce avoiding the vertex area [6]) mainly for beam launcher optics to be small (1-2cm) and for centering and dithering reasons. The vertex area requires custom fine polishing of edges and peaks of the prisms.

4. MULTIPLE CORNERCUBES GEOMETRIES

Multiple cornercube assemblies (MCC) can have various geometrie as shown in figure 1. Later we will describe a triple corner cube (TCC) system made with four prisms. The very first of all MCC's shown in figure 1a is obviously a simple CC. With two corners we can form a Dual CC (DCC) made with at least 3 prisms. Figure 1e shows a real back to back DCC where the vertex can see areas 180deg apart. For manufacturability reasons we prefer the case where both corners have a common roofline. This is shown in figure 1b,c,d where the wedge angles is given by the basic angle 30deg, 50deg and 90deg between the corners. We can express the second corner as the first corner rotated by the wedge angle + 90deg. Let us call β the wedge angle. When we augment even more the wedge, we fall again in case 1b.

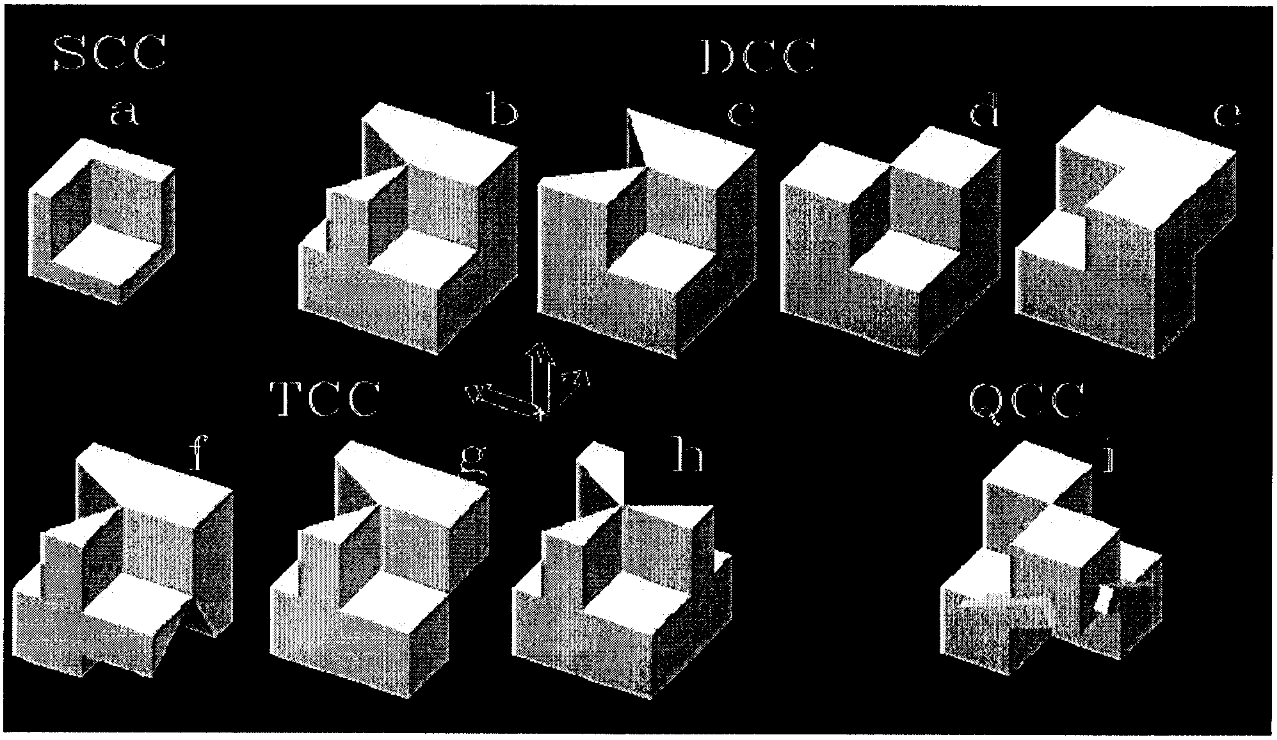

Figure 1: Multiple cornercube geometries with 1,2,3,4 corners

With 3 corners, we can form a very large number of TCC's. We can take the previous DCC's and apply another rotation to generate the new corner. This rotation can be orthogonal to the first rotation. A large family of TCC's can be represented with two orthogonal rotations of angles the basic wedge angles β and δ augmented by 90deg. Let us suppose that the first corner (the 'upper right' corner) is Oxyz, pointing along vector [1,1,1]. Then the 'upper left' and the 'lower'corner would be defined respectively by:

$$\mathbf{R}_{ulc} = \begin{vmatrix} \cos(90+\beta) & \sin(90+\beta) & 0 \\ -\sin(90+\beta) & \cos(90+\beta) & 0 \\ 0 & 0 & 1 \end{vmatrix} \quad \beta \geq \sim 20^\circ \qquad \mathbf{R}_{lowerc} = \begin{vmatrix} \cos(90+\delta) & 0 & \sin(90+\delta) \\ 0 & 1 & 0 \\ -\sin(90+\delta) & 0 & \cos(90+\delta) \end{vmatrix} \quad \delta \geq \sim 20^\circ$$

Figure 1f shows the general case of a TCC with random wedge angles. The TCC in figure 1g is a preferred particular case where basic angles are β=30deg and δ=90deg convieniently. From now on we will refer the $TCC_{\beta=30,\delta=90}$ as *the* TCC. As for the DCC's the wedge angle can augment up to 90deg. Three corners can be arranged in other ways. A straightforward variation is the mirrored version (the left hand TCC). A rotationally symetric design is the pieslice or flower type, shown in figure 1h, where three 30deg wedges are positioned on one single flat. The TCCflower's acceptance zones look like three sectors in a half upper hemisphere. It was found that it was the only solution for older designs for SIM for the outermost fiducial. Another imagined type of MCC is the Quadruple CC (QCC). A QCC can exist mathematically but is difficult to build and needs external brackets. It totalizes most FOV. Other exotic systems have been imagined but for most applications in interferometry and possibly industrial metrology, a set of the shown SCC, DCC, TCC's should suffice. In all cases, basic angles of the wedges are degrees of freedom available for the designer. For the TCC, δ is preferably 90deg and β can be anywhere between about 20 and 90 degrees. But, at all times, the angle α of the large wedged prism must be α=180-β deg for angle closure reasons.

5. THE TRIPLE CORNERCUBE

For earlier versions of SIM and the MAM, a reference tetrahedron was monitoring a set of about 7 non-equidistant fiducials aligned on the siderostats axis situated at some distance for SIM and closer for the MAM. For MAM the reference structure was also supposed to see 3 points 180deg away (artificial stars) which made the MCC design harder. The TCC concept has been tried on many geometries and was found to be successful, due to interesting angular combinations of the three FOV's. Actually the TCC can be regarded as a very multipurpose design. For various truss geometries (as the design of SIM evolved and will still evolve), for most fiducials, a TCC with specific attitudes and wedge angles could see other points with reasonable incident angles (frequently 5 to 10deg only). Sometimes the (initially arbitrary) tetrahedron was deformed to allow less grazing angles into the TCC. A program has been written to find solutions with a Monte Carlo algorithm and optimize attitudes to obtain reduced grazing angles.
For the current design of SIM, TCC's have been tried in fist place. The current design is an adjustable pair of pods with maximal baseline about 10m. Each pod contains 4 telescopes (or compressors) [1] looking at the same central fiducial point, imitating the geometry of an Indian teepee with only 4 axis. A TCC located at the vertex is able to see the 4 telescopes (as well as the other TCC) provided telescopes are regrouped enough in FOV to avoid blind zones of the TCC. The FOV must account for the ± 7.5deg circular excursion of the telescopes. If all telescope are in a FOV of ~60deg, then they can be seen by only one corner. An influent parameter is the size of the metrology beams to be returned and whether we accept minor vignetting for outermost beams or not.

TCC version:	glass	facet size	surf figure PV.633	prism accy	other
Prototype (97)	ULE	3cm	λ/5	3 arcsec	
Future (mid98)	ULE	3cm	λ/20	1 arcsec	no bevels no roll-off ablation

Note: corner accy and NCVE depend on assembly

Figure 2: Specifications of the TCC prisms (prototype and current version)

We decided to design and build a TCC because it satisfies MAM and SIM and offers a lot of polyvalence in general.
The first assembly –the prototype- was made out of ULE from Corning with 30mm facet prisms. Specifications are listed in figure 2 and the arrangement and allure of the assembly is shown in figure 3

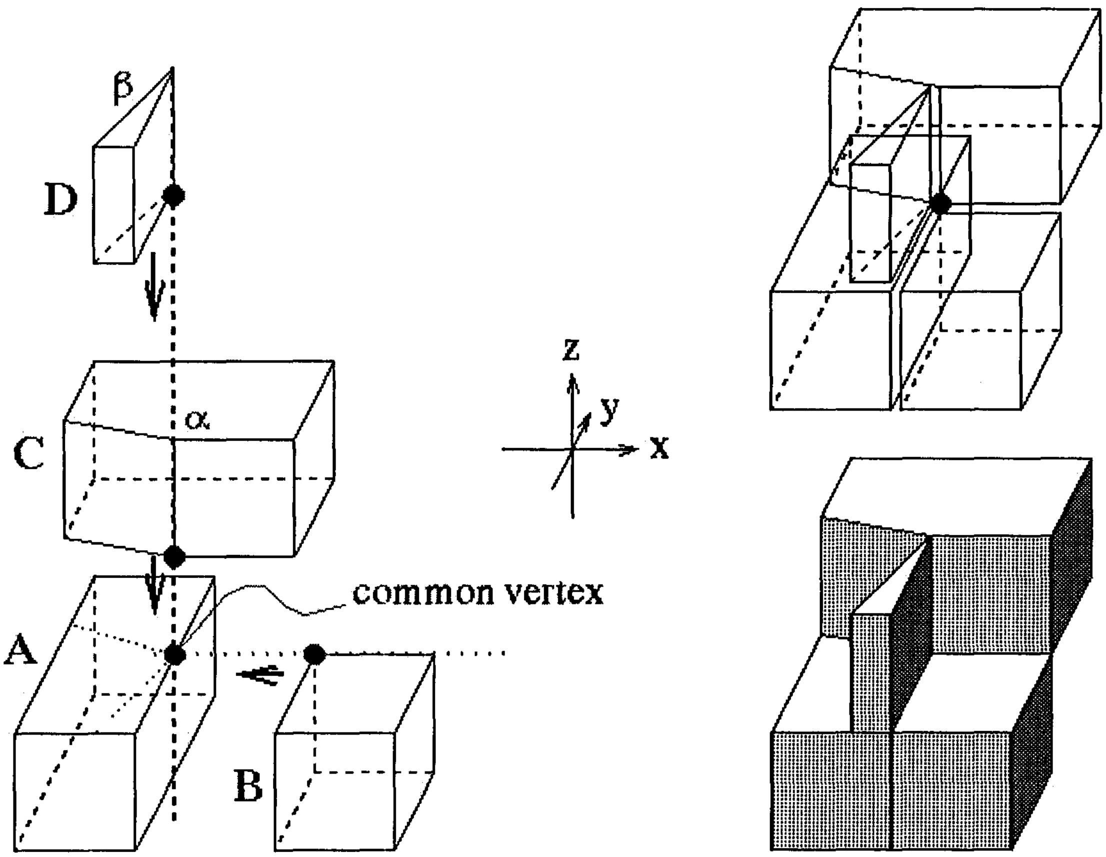

Figure 3: Assembly of the 4 prisms of the TCC. This forms 3 corners with one common vertex

The 4 different prisms are:

A: Rectangular box 2e*e*e.
B: Cube e*e*e.
C: rectangular wedged box 2e*e*e with angle $\alpha = 150$deg
D: Thin wedge prism with face e*e and with angle $\beta = 30$deg

The prisms B and C are complementary, so $\alpha+\beta$ must be 180deg, but α itself is not critical. A number of 11 designated faces must be polished and 9 of them must be reflective (Al) coated. Surface figure was requested $\lambda/5_{PTV,\ 633nm}$. Bevels were large for the prototype, frequently 1/4 mm.
Moderate prism accuracy was requested mainly because a first assembly was needed rapidly to prove the concept

6. ASSEMBLING & RESULTS

The method of assembling the TCC would deserve an entire paper itself. Briefly the retroreflector is assembled under real time multiwavelength (white light and HeNe) interferometric monitoring. A 6-axis PZT micropositionning system with remote control (to avoid turbulence and hand-effect) brings consecutively prisms B,C,D onto A in 4 basic steps. All 90deg roofs and corners can be aligned and checked with HeNe beams while the vertex of the 3 corners can be brought to a common point with a rotary stage and an absolute metrology beam sensing facets and roofs. Frequently two interferometers where running simultaneously to satisfy the large number of degrees of freedom at each step.

Interferometric methods can easily detect errors at the arcsec/µm level. A relation to keep in mind is: 1arcsec x 30mm = 0.15µm = $\lambda_{HeNe}/4$ = 2 fringes. For assembling, a UV glue was used. We chose the well proven NOA61 from Norland. We did not favor pure optical contact because we believe its strength is not reliable and high DOF alignement is difficult. We preferred bonding the prisms with UV curing glue. When correct angles -as well as correct pistons- were achieved, UV radiation was sent though the glass. A layer of ~20µm of NOA61 from Norland™ was satisfactory. Prisms were then defixtured and new roof cavities were measured. An error occurred once which needed decementing. Finally the prototype was assembled successfully in June 1997.,see figure 4 , taking only one year from the original idea to complete realization of a prototype, including design and construction of the assembling setup.

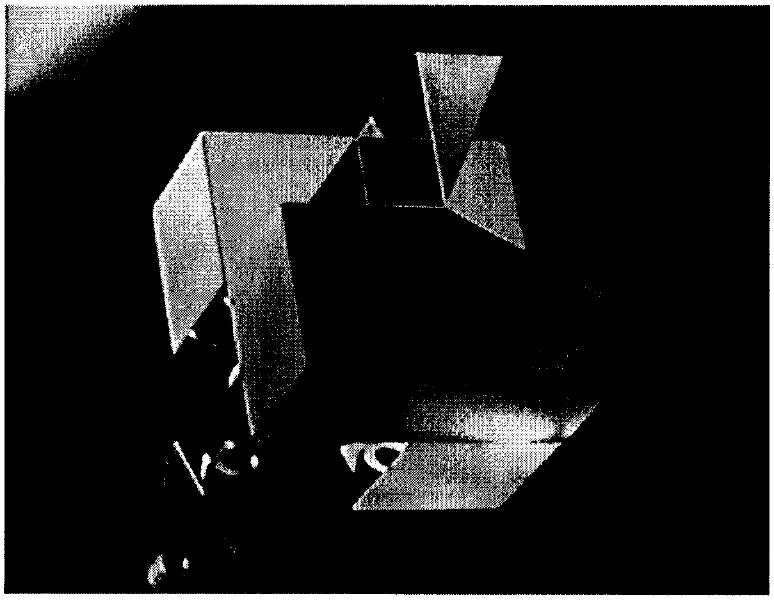

Figure 4: photograph of the TCC prototype

A relative good optical quality has been obtained: Zygo™ Interferograms of corners (in single pass) are shown in figure 5. Corners show ~1 wave $_{PTV,633nm}$ for 2 corners and ~1/3 wave $_{PTV,633nm}$ for the third. This accounts a 50mm full hexagonal aperture, much more than a 5mm beam, even oblique. The error is dominated by dihedral errors and not by surface figure in this first assembly.

On these first prisms, roll-off was strong on some edges. This, together with the 3arcsec angles and λ/5 general surface accuracy, rendered alignement harder. Errors also come from inaccuracies in the constructing interferometers (a Michelson and a small PDI) by far not as good as the Zygo. Another contribution is glue variations at curing (some shrinkage drift could be compensated) and also post curing. Aging test will be done in the future by monitoring roof samples.

As for the space qualification of the TCC, bonding does not seem to be a problem. Computations made by K.Aaron at JPL have shown that the TCC should withstand launch forces: If we consider a 1 inch square area for a=500g, we have:

$$\sigma = F / S = \rho_{glass} L^3 a / S \sim 80 \text{ psi}$$

$$\sigma_{max,\ adhesive} \sim 1500 \text{ psi} \qquad \text{Hence:} \qquad FS \sim 15$$

The non common vertex error (NCVE) of the prototype was found to be a few µm (radius estimated at 2 µm) in plane as measured with the same top quality rotary stage as at assembling (the runout/wobble performance is in the µm/arcsec range). In the future, I believe that a NCVE of 1 µm or less should be achieved, rexating the requirement 'attitude-drift' of the TCC.

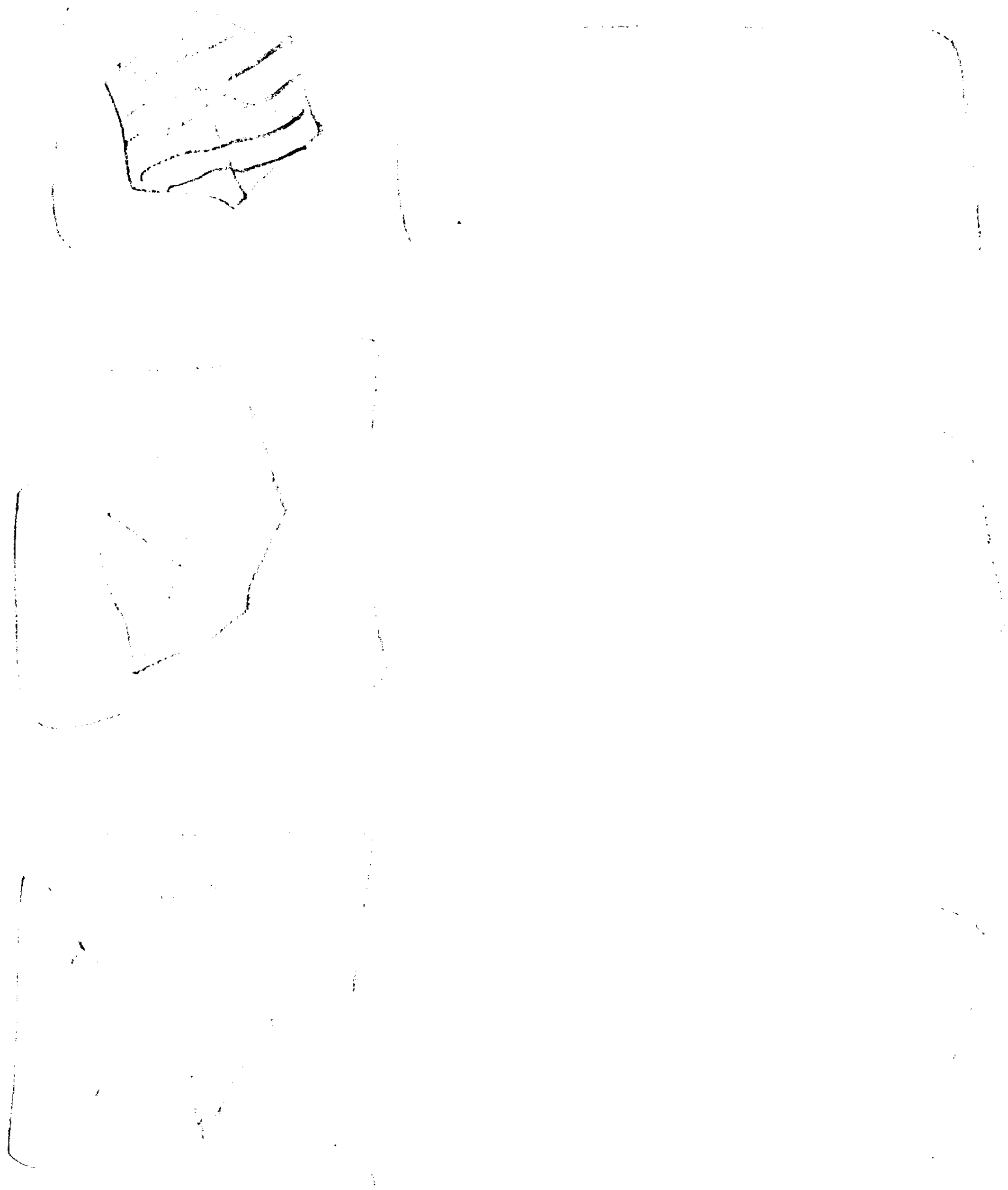

Fig 5 2 Views of the 2 cameras

7. FUTURE VERSIONS

Future assemblies will require higher or state-of-the-art precision up to the ultimate use in SIM.
A new version is currently being prepared by a local company (Precision Optical). Polishing is still ongoing hence assembly has not started yet. Specs are tighter than the prototype as shown in figure 2. Critical angles are now 1 arcsec and bevels 50μm or less. Unchanged will be the material (ULE) and the basic size (e=30mm). The design itself will not change except that a recess area idea will be explored. An ablation technique has been tried and was successful. This will reduce the effect of the bad CTE of UV curing epoxies (~100ppm/C) as soon as prisms come in contact. Contact (helped by shrinkage at cure) would also reduce the out-of-plane NCVE from about 20μm to zero. It is not well known if contact is really desirable because it may stress and deform the optics. For diffraction concerns, gaps of 0 or a few μm's would not make a big difference.
It is important to note that an interesting athermal feature of the TCC concept is that when glue expands, the vertex is *invariant*, hence conserving common vertex.
The soon to be assembled TCC will be used for MAM in real vacuum conditions and under subnanometer laser metrology. This will provide good opportunities to study the impact of non perfect corners and NCVE on metrology performance.

8. CONCLUSION

This paper describes the pioneering work at JPL on the innovative Triple Corner Cube with common vertex, developed for the needs of space interferometry. A prototype has been successfully constructed. A relatively good optical quality has been obtained in terms of corner errors and NCVE. It is shown that the current design of TCC is multipurpose ie suitable for various geometries of optical trusses to accommodate multiple designs in SIM. A high quality version is being prepared nowadays for MAM with the experience gained building the prototype. Our experience in assembling optics to the sub-fringe level will be useful in the future for other critical optical components as well.

9. AKNOWLEDGEMENTS

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